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Key Points:

- Storage sensitivity of streamflow expresses the change in streamflow per change in water storage
- Differences in streamflow sensitivity to storage changes are quantified for 725 European catchments
- Storage sensitivity of streamflow is positively correlated with flow variability in our study region

Supporting Information:

- Texts S1–S3 and Figures S1 and S2

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Streamflow sensitivity to water storage changes across Europe

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Abstract Terrestrial water storage is the primary source of river flow. We introduce storage sensitivity of streamflow (ϵ_S), which for a given flow rate indicates the relative change in streamflow per change in catchment water storage. ϵ_S can be directly derived from streamflow observations. Analysis of 725 catchments in Europe reveals that ϵ_S is high in, e.g., parts of Spain, England, Germany, and Denmark, whereas flow regimes in parts of the Alps are more resilient (that is, less sensitive) to storage changes. A regional comparison of ϵ_S with observations indicates that ϵ_S is significantly correlated with variability of low ($R^2 = 0.41$), median ($R^2 = 0.27$), and high flow conditions ($R^2 = 0.35$). Streamflow sensitivity provides new guidance for a changing hydrosphere where groundwater abstraction and climatic changes are altering water storage and flow regimes.

1. Introduction

Climate change and direct anthropogenic impacts on the water cycle are altering river flow regimes, thereby affecting water resources and natural hazards [*Stahl et al.*, 2010; *Montanari et al.*, 2013]. The magnitude of hydrologic change depends both on the change in forcing (e.g., climate conditions and groundwater use) and the catchment's sensitivity to these changes. Exposing this sensitivity helps characterize the hydrologic functioning and can support water management strategies and climate change impact assessments [*Prudhomme et al.*, 2010; *Botter et al.*, 2013].

A widely used hydrologic sensitivity measure is climate elasticity of streamflow, which expresses a catchment's annual or seasonal streamflow change per change of climatic condition (e.g., rainfall, temperature, potential evaporation, and snow fraction) [*Schaake*, 1990; *Nijssen et al.*, 2001; *Sankarasubramanian et al.*, 2001; *Vano et al.*, 2012; *Berghuijs et al.*, 2014a]. Climate elasticity is useful as it exposes where river flow is most sensitive to change, without the use of highly parameterized models, and independent of the uncertainty of future climatic conditions.

For instantaneous streamflow the development of a similar parsimonious expression for streamflow as a function of precipitation rates (or other climate conditions) is hindered by the temporal disparity between meteorological conditions and consequent streamflow response; similar-sized rainfall events can lead to orders of magnitude difference in runoff coefficients, depending on antecedent wetness conditions [*Tromp-van Meerveld and McDonnell*, 2006]. Although precipitation intensity controlled runoff-generating processes that can be observed during periods of rainfall [*Dunne*, 1983], for many catchments subsurface water storage is for the majority of time the main driver of streamflow response [*Spence*, 2010; *McNamara et al.*, 2011; *Riegger and Tourian*, 2014]. There are regional differences in the estimated volume and timescale of the subsurface contributions to streamflow [*Beck et al.*, 2013]. Both climatic changes and variations, and human groundwater abstractions are affecting groundwater storage around the globe [*Green et al.*, 2011; *Taylor et al.*, 2013; *Döll et al.*, 2014; *Richey et al.*, 2015; *Gleeson et al.*, 2015], but a theory that exposes the sensitivity of flow to storage changes across diverse landscapes and spatial scales is currently not exploited.

Here we introduce storage sensitivity of streamflow (ϵ_S), which is a measure of the sensitivity of streamflow to changes in catchment-scale water storage. We use hydrograph recession analysis [*Brutsaert and Nieber*, 1977; *Tallaksen*, 1995] which allows us to express a catchment's storage-driven streamflow response to water storage change [*Kirchner*, 2009]. For 725 mostly nonregulated catchments across Europe we (i) calculate hydrograph recession characteristics, (ii) expose how hydrograph recession characteristics lead to differences in ϵ_S between catchments, and (iii) expose the regional patterns in ϵ_S whereby we identify for which catchments the flow regimes are more sensitive to water storage changes. Both meteorological forcing and how the landscape filters this meteorological forcing determine regional differences in flow regimes [*Botter et al.*, 2013; *Berghuijs et al.*, 2014b]. To assess to what degree a catchment's storage sensitivity of streamflow influences regional differences in flow regimes, we (iv) compare ϵ_S with the slope of different parts of the flow duration curve (FDC) [*Vogel and Fennessey*, 1994].

2. Data

We use daily streamflow values covering a maximum time period of 1863–2008 from 725 catchments (Supporting Information Text S3); most of the records are part of the United Nations Educational, Scientific and Cultural Organization's (UNESCO) European Water Archive, which includes data provided by the European subnetwork (EURO-Flow Regime from International Experiment and Network Data (FRIEND), http://ne-friend.bafg.de) of the international research project FRIEND, which is maintained by the Global Runoff Data Centre (http://grdc.bafg.de). French and Spanish discharge time series were accessed via the French water agency (Eaufrance, http://hydro.eaufrance.fr/) and the Spanish Centre for Civil Engineering Studies and Experimentation (ceh-flumen64.cedex.es). Catchments range in size from 5 to 6133 km^2 (median = 237 km^2), in mean elevation from 12 to 2659 meters above sea level (MASL) (median = 662 MASL), in precipitation from 398 to 2603 mm/a (median = 853 mm/a), and in mean annual temperature from -2 to 16°C (median = 8°C). A few of the 725 catchments show large gaps in their observed time series (up to 77% missing data), but 90% of them have $<$10% of missing data. Most of these data have been used in several studies before, including a subset of long-term records without gaps suitable for low flow analysis, which has been used to study streamflow trends empirically [*Stahl et al.*, 2010], to make comparisons with modeled runoff from the Water and Global Change model ensemble [*Gudmundsson et al.*, 2012] or as part of a larger data set used for the interpolation of runoff across Europe [*Gudmundsson and Seneviratne*, 2015].

3. Methods

3.1. Storage Sensitivity of Streamflow

Storage sensitivity of streamflow, ϵ_S, is defined as the change of instantaneous normalized streamflow, dQ/Q (dimensionless), divided by the change in instantaneous catchment-scale water storage, dS (mm)

$$\epsilon_S = \frac{\mathrm{d}Q/Q}{\mathrm{d}S} \tag{1}$$

An ϵ_S value of $X\,\mathrm{mm}^{-1}$ thereby indicates that 1 mm increase in water storage results in a fractional increase of X (dimensionless) in streamflow. ϵ_S is a measure of the sensitivity of instantaneous flow values to water storage changes and does not incorporate any effects of other runoff generation processes.

3.2. Analytical Approximation ϵ_S

When water storage is the only source of streamflow, log-log plots of streamflow Q and the recession rate dQ/dt show often an approximately linear correlation between the variables, suggesting a power law relationship [*Brutsaert and Nieber*, 1977]

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = -\alpha \cdot Q^{\beta} \tag{2}$$

where Q is streamflow (mm/d), dQ/dt is streamflow recession (mm/d^2), α is a coefficient ($\mathrm{mm}^{1-\beta}\,\mathrm{d}^{\beta-2}$), and β is an exponent (dimensionless). *Kirchner* [2009] shows that from (2) the change in streamflow per change in water storage can be expressed as

$$\frac{\mathrm{d}Q}{\mathrm{d}S} = \frac{\mathrm{d}Q/\mathrm{d}t}{\mathrm{d}S/\mathrm{d}t} = \frac{-\alpha \cdot Q^{\beta}}{-Q} = \alpha \cdot Q^{\beta-1} \tag{3}$$

Hydrograph recessions used to derive α and β here are similar to *Ye et al.* [2014]; we use the 3 day moving average of a hydrograph, recession periods have a minimum of 10 days, and the first three days of a falling limb are eliminated from the recession period (to reduce any effect of precipitation and fast runoff processes). Hydrographs are selected for the winter period only to reduce the influence of evaporation [*Federer*, 1973; *Wittenberg and Sivapalan*, 1999; *Kirchner*, 2009]. Recessions that are interrupted by missing data are removed from the analysis. With a linear regression of log-log plots between streamflow Q and the recession rate dQ/dt we calculate α and β

$$\ln(Q_{t-1} - Q_t) = \ln\alpha + \beta\ln\left(\frac{Q_t + Q_{t+1}}{2}\right) \tag{4}$$

where t is the tth day of a recession record. Storage sensitivity of streamflow can now be calculated by

$$\epsilon_S(\alpha,\ \beta,\ Q) = \ \alpha\cdot Q^{\beta-2} \tag{5}$$

where ϵ_S is a function of the flow rate of interest (Q) and α and β can both be derived from streamflow observations. Because ϵ_S is derived from recession periods, it can be quantified for almost any catchment. The use of ϵ_S is thereby not constrained to catchments where during the entire hydrograph streamflow is water storage driven (which is the case in *Kirchner* [2009]).

ϵ_S can also be calculated while relaxing the assumption that the relationship between streamflow recession (dQ/dt) and streamflow (Q) is well summarized by the *Brutsaert and Nieber* [1977] approach (equation (2)) and instead allowing this relationship to take any shape. In this more general case no analytical solution for ϵ_S exists. The calculated ϵ_S in the general case are very similar to those obtained by the analytical equation (5) (see Supporting Information Text S1).

3.3. Comparison of ϵ_S With Historical Flow Variability

ϵ_S is a (state-dependent) catchment characteristic that expresses how a catchment responds to water storage changes. ϵ_S does not include any information on the actual flow regime directly; without water storage variations a highly sensitive catchment can still have a very constant flow regime. To assess if ϵ_S is an important control on the actual streamflow variability that occurs across the study sites, we compare regional differences in slopes of the flow duration curve against ϵ_S values. The flow duration curve is a plot that shows the percentage of time that flow in a stream is equal or exceeds some specified value of interest [*Vogel and Fennessey*, 1994]. If storage sensitivity of streamflow is an important control on the observed streamflow variability, we expect regional differences in slopes of the flow duration curve to be positively correlated with regional differences in ϵ_S values. If there is limited correlation between the two metrics, other factors are deemed to be more important for a catchment's flow duration curve, such as flow regulation, climate variability, or precipitation-driven streamflow generation. Similar to *Hartmann et al*. [2013], we calculate the slope of the flow duration curve for low flow conditions ($S_{\mathrm{FDC}}(Q_{75,}Q_{95})$), median flow conditions ($S_{\mathrm{FDC}}(Q_{40,}Q_{60})$), and high flow conditions ($S_{\mathrm{FDC}}(Q_5,Q_{25})$)

$$S_{\mathrm{FDC}}\left(Q_{\mathrm{i}}, Q_{\mathrm{j}}\right) = \frac{\ln(Q_i) - \ln\left(Q_j\right)}{(i-j)} \tag{6}$$

where S_{FDC} is the slope of the flow duration curve (dimensionless) and i and j are the percentiles of exceedance.

4. Results

The α and β values vary across the 725 catchments (Figure 1). The β values show regional differences, indicating that the curvature of storage-discharge relationships varies among the catchments. The β values determine the shape of the storage-discharge function; a storage-discharge relationship for $\beta < 1$ is concave, indicating that increased water storage leads to a slowing increase in streamflow. Concave storage-discharge relationships are not abundant (35/725), and most of them occur in Spain. For $\beta = 1$ the storage-discharge relationship is linear, indicating that discharge increases linearly with a storage increase. For $1 < \beta < 2$ the storage-discharge relationship is convex, which is observed in the majority of catchments (633/725). For $\beta = 2$, ϵ_S is constant and equal to α. For $\beta > 2$ (57/725 catchments) ϵ_S increases (goes to infinity from zero) as discharge decreases. The α values scale the slope of the storage-discharge relationship; a larger α value indicates a steeper slope of the storage-discharge relationship, for a given value of β. However, because of α's dependency on β (see units), a direct comparison of α values without considering the associated β values is not meaningful. Since each α value combines information on the magnitude of Q as well as the value of β, no physical interpretation can be placed on the spatial patterns of α.

Based on equation (5), we can calculate the sensitivity of streamflow to storage changes, $\epsilon_S(\alpha, \beta, Q)$, where α and β are the assigned values of the catchment displayed in Figure 1 and Q can be set at any value of interest.

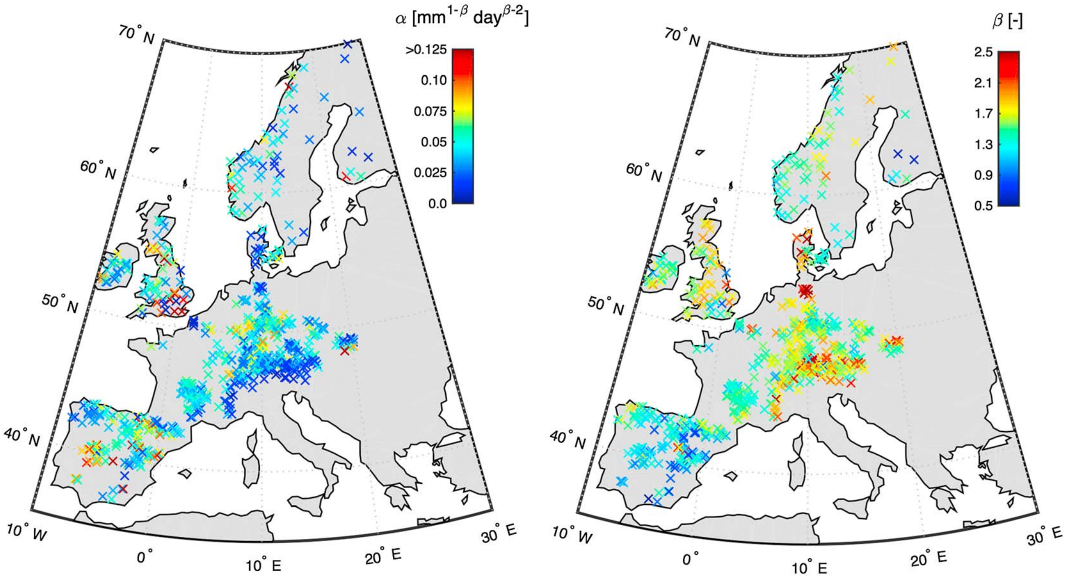

Figure 1. The α (mm$^{1-\beta}$ d$^{\beta-2}$) and β (dimensionless) values for the 725 catchments. (NB: no physical interpretation can be placed on the spatial patterns of α.)

As exemplified for three different flow values that occur in the vast majority of catchments ($Q = 0.1$ mm/d, $Q = 0.5$ mm/d, and $Q = 1.0$ mm/d), the storage sensitivity of streamflow varies strongly across catchments (Figure 2); ϵ_S shows orders of magnitude difference in the streamflow response to a given storage change, depending on α and β values and the flow rate.

This highlights differences in storage-discharge relationships of catchments, but the sensitivity of the flow regimes to storage changes also depends on the flow values that occur. ϵ_S is calculated for low flow (Q_{85}), median flow (Q_{50}), and high flow (Q_{15}) conditions of the individual catchments (Figure 3). The sensitivities vary per part of the flow regime and per catchment. ϵ_S is on average higher for the low flow values (median $\epsilon_S = 0.062$) than for median flow values (median $\epsilon_S = 0.038$) and high flow values (median $\epsilon_S = 0.023$). In some cases Q_{15} exceeds the maximum observed streamflow of the hydrograph recessions, but this is only the case for a limited number of catchments (79/725). For all parts of the flow regime, ϵ_S is generally highest in many catchments in Spain, in parts of England and Germany, and the Danish island of Zealand, whereas catchments in the southern parts of the Alps are most resilient to water storage changes.

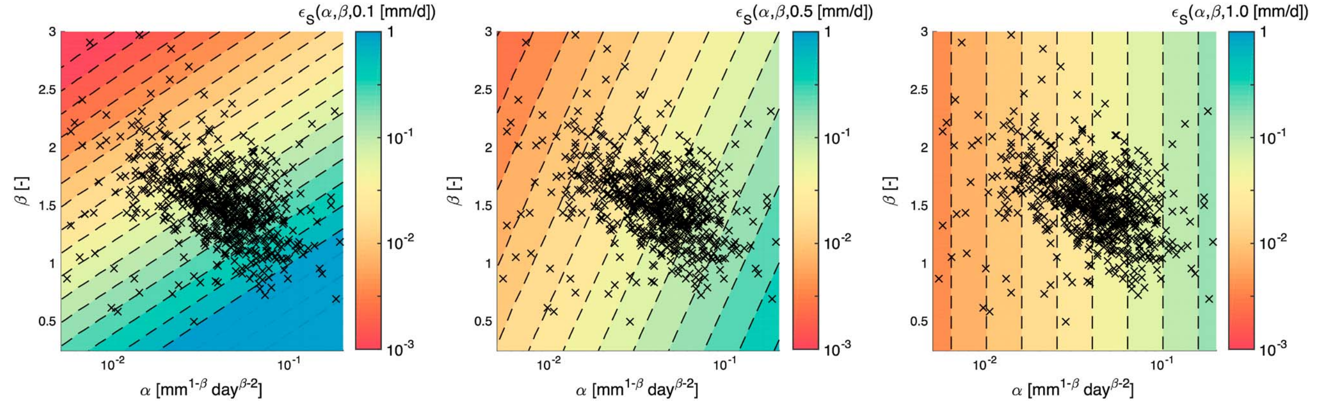

Figure 2. Storage sensitivity of streamflow (ϵ_S) for three different flow values: (left) $Q = 0.1$ (mm/d), (middle) $Q = 0.5$ (mm/d), and (right) $Q = 1.0$ (mm/d). The catchments' α (mm$^{1-\beta}$ d$^{\beta-2}$) and β (dimensionless) values are indicated by black markers. (NB: it is only meaningful to compare α values between catchments when their β values are the same.)

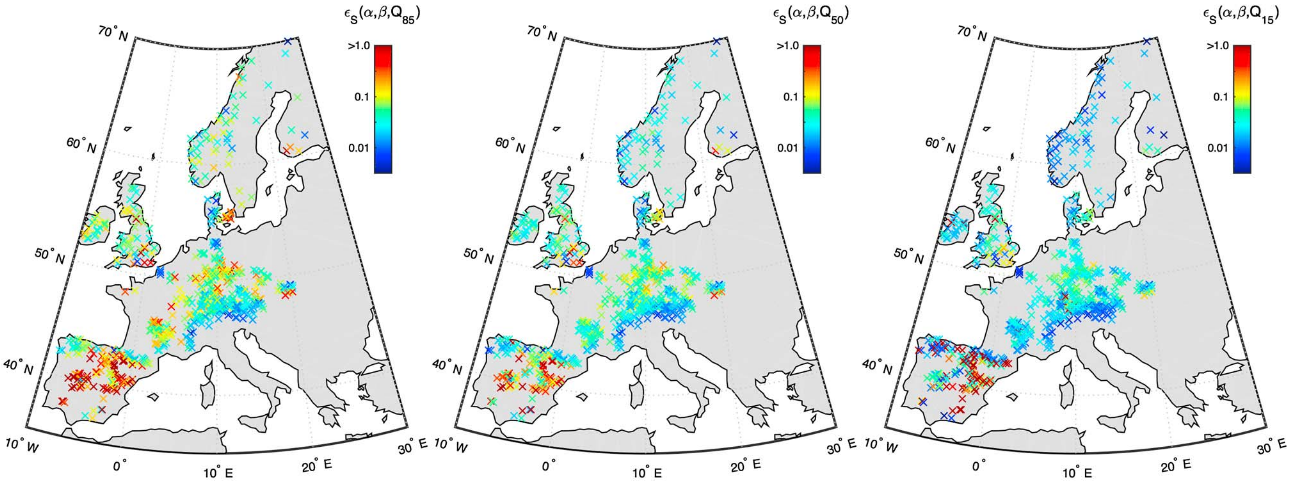

Figure 3. The storage sensitivity of streamflow (ϵ_S) for low flow (Q_{85}), median flow (Q_{50}), and high flow (Q_{15}) conditions.

The slopes of flow duration curves are empirically related to storage sensitivity across catchments for three streamflow regimes: low, median, and high flows (Figure 4). The degree of correlation in log-log space between ϵ_S and slopes of the flow duration curve for low ($R^2 = 0.40$, p value < 0.001), median ($R^2 = 0.27$, p value < 0.001), and high ($R^2 = 0.35$, p value < 0.001) flow values suggests that the sensitivity of streamflow to storage changes partly controls the historical variability of the flow regime.

5. Discussion

Streamflow sensitivity to water storage changes has been used before as part of an analysis of two catchments in Wales [*Kirchner*, 2009], but that study did not explicitly focus on streamflow sensitivity per se nor as a diagnostic of vulnerability. The relative changes in the flow per unit of water storage change provide a parsimonious hydrological model, with parameters directly derivable from streamflow observations, that quantifies the sensitivity of instantaneous storage-driven flow values to water storage changes. Other modeling approaches often need additional data and longer time series to calibrate the model [*Melsen et al.*, 2014]. Predictions of low flow conditions are often based on multimodel assessments [e.g., *Prudhomme et al.*, 2014] that have large uncertainty in parameters related to subsurface runoff generation [*Hou et al.*, 2012; *Huang et al.*, 2013] and do not provide efficient guidance in understanding regional landscape differences.

Storage-discharge relationships form the basis of the derived streamflow sensitivity. Yet single α and β are not a perfect characterization of the drainage properties of a catchment; the power law coefficient, α, and

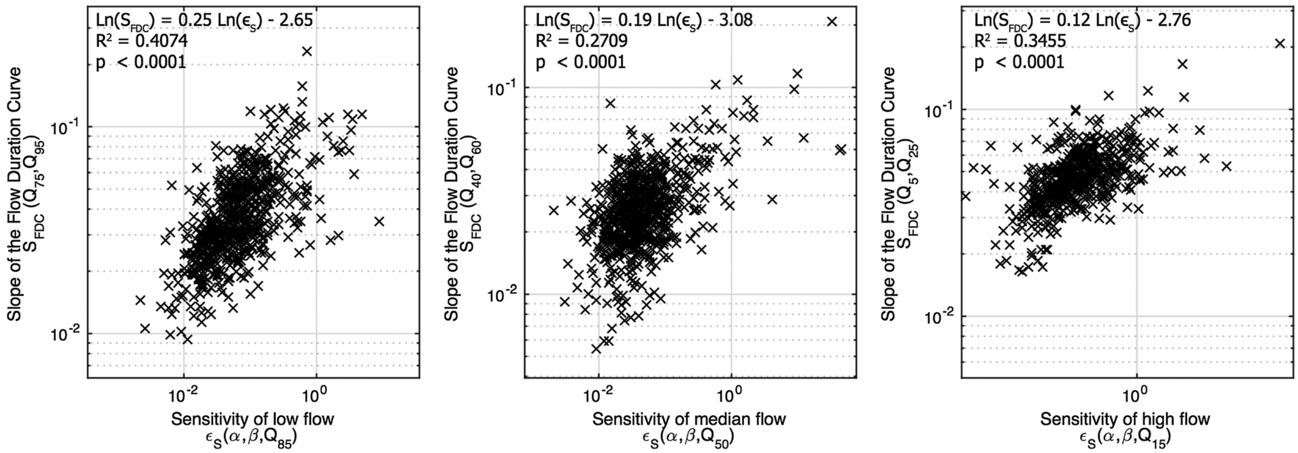

Figure 4. Scatterplot of the storage sensitivity to streamflow (ϵ_S) for low flow ($\epsilon_S(Q_{85})$), median flow ($\epsilon_S(Q_{50})$), and high flow ($\epsilon_S(Q_{15})$) conditions and associated slopes of the flow duration curves for low ($S_{FDC}(Q_{75},Q_{95})$), median ($S_{FDC}(Q_{40},Q_{60})$), and high ($S_{FDC}(Q_5,Q_{25})$) flow conditions.

the exponent β can vary with the chosen methodology [*Rupp and Selker*, 2006; *Stoelzle et al.*, 2013; *Dralle et al.*, 2015; *Thomas et al.*, 2015], spatial variation of rainfall and groundwater discharge [*Biswal and Nagesh Kumar*, 2014], and the quality of data [*Rupp and Selker*, 2006; *Stoelzle et al.*, 2013]. Questions still remain about whether the α parameter is a meaningful way to summarize recession behavior. Further refinements of hydrograph recession analysis will continue to be the topic of future studies, whereby refined methods can be implemented in calculations of storage sensitivity. The example provided is already informative by exposing for the first time strong regional differences in storage sensitivity of streamflow across Europe. The method can be immediately implemented in other catchments where streamflow observations are available. The data used in this study are from near-natural catchments across Europe. However, streamflow sensitivity to water storage changes characterizes the catchment's hydrologic functioning given its current land use and anthropogenic conditions, and in theory could be applied to systems with strong human influence, provided that discharge is still controlled by storage.

The imperfect fit between ϵ_S and slopes of the FDC indicates that other factors, such as regional differences in climatic variability [*Gudmundsson et al.*, 2011; *Berghuijs et al.*, 2014b], nonstorage-related runoff-generating mechanisms [*Dunne*, 1983], and human influences [*Poff et al.*, 2007; *Jaramillo and Destouni*, 2015], are also important for the nature of the catchment's flow regime. However, independent of its uncertainties and unaccounted factors, ϵ_S still explains a significant part of the flow variability between places indicating that the storage-discharge relationships of the catchments partly determine the nature of flow regimes. This suggests that how a catchment filters water storage is an important factor in regional differences of flow regimes. Unexplained variability will be caused by regional climate differences, overland flow, snowmelt, and uncertainties associated with the used sensitivity characterization. Predicting streamflow sensitivity to storage changes by landscape (catchment area, mean elevation, mean slope, and lithology) or climate descriptors (annual precipitation and mean temperature) remains a difficult task. Only precipitation ($r = -0.25$, p value < 0.001) and temperature ($r = 0.29$, p value < 0.001) provide significant correlation (see Supporting Information Text S2). Catchment aridity gives a similar correlation as catchment precipitation, and thus, the inclusion of potential evaporation does not (appear to) improve the link with sensitivity values. Missing information on, for example, the aquifers' volume, residence time, and spatial organization may help to further explain regional differences in streamflow sensitivity.

Projections of future changes to the flow regime are available [e.g., *Arnell*, 1999; *Schneider et al.*, 2013; *Hagemann et al.*, 2013; *Prudhomme et al.*, 2014] but are strongly affected by uncertainties in precipitation predictions, model representation, and water abstractions [*Beven*, 2008]. Independent of the uncertainties in future climate and water use conditions, streamflow sensitivity to water storage changes helps identify which regions are most resilient or vulnerable to climatic shifts and other water storage affecting factors. The sensitivity of flow regimes thereby shows orders of magnitude differences within Europe (Figure 3). The regional differences of streamflow sensitivity to water storage changes have not been reported before in scientific literature and provide guidance to those places that are most sensitive to water storage changes, independent of their cause. As the landscape and hydrologic features that control sensitivity are not exposed by our method, more in-depth site research should expose the causes of sensitivity values, thereby providing additional information often critical for local decision-making.

6. Conclusions

We developed a method to quantify a catchment's streamflow sensitivity to water storage changes. This storage sensitivity of streamflow can be approximated by an analytical equation that is a function of the flow rate of interest and Brutsaert-Nieber recession parameters that can be directly derived from hydrograph recession analysis. The streamflow response we obtain by the α and β values derived for 725 catchments across Europe (Figure 1) can have several orders of magnitude to a given flow change, depending on α and β values and the flow rate (Figure 2). The storage sensitivity to streamflow for low flow ($\epsilon_S(Q_{85})$), median flow ($\epsilon_S(Q_{50})$), and high flow ($\epsilon_S(Q_{15})$) conditions shows strong regional differences in sensitivity to water storage changes (Figure 3). Although the regional differences vary between the flow percentiles, some regions stand out as being more sensitive to water storage changes. The sensitivities are generally highest in many catchments in Spain, in parts of England and Germany, and the Danish island of Zealand, indicating these regions are most sensitive to water storage changes. The most resilient regions to water storage changes are the catchments in the southern part of the Alps. A comparison of sensitivity values with different parts of the flow duration curve indicates that ϵ_S, without any information on climate variability and nonstorage-driven runoff, explains some of the differences between catchments in the variability of the low, median, and high flow spectra. The distinction of different sensitivities to water storage changes provides a novel indicator for hydrologic resilience to climatic perturbations and anthropogenic water use, which can be valuable in improving water management strategies and decision-making in times of global change.

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